Chapter 8
Design of J-PARC Transmutation Experimental Facility

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Abstract After the Fukushima accident caused by the Great East Japan Earthquake, nuclear transmutation acquired much interest as an effective option of nuclear waste management. The Japan Atomic Energy Agency (JAEA) proposes the transmutation of minor actinides by an accelerator-driven system (ADS) using lead–bismuth eutectic alloy (Pb-Bi) as a spallation target and a coolant of the subcritical core. The current ADS design has 800 MWth of rated power, which is driven by a 20 MW proton LINAC, to transmute minor actinides generated from 10 units of standard light water reactors.

To obtain the data required for ADS design, including the European MYRRHA project, JAEA plans to build a Transmutation Experimental Facility (TEF) within the framework of the J-PARC project. TEF consists of two buildings: one is an ADS target test facility (TEF-T), in which will be installed a high-power Pb-Bi spallation target, and the other is the Transmutation Physics Experimental Facility (TEF-P), which will set up a fast critical/subcritical assembly driven by a low-power proton beam. TEF will be located at the end of the 400 MeV LINAC of J-PARC and accept a 250-kW proton beam with repetition rate of 25 Hz. As major research and development items of TEF-T, irradiation tests for structural materials and engineering tests for Pb-Bi applications to determine the effective lifetime of the proton beam window will be performed. The reference design parameter, that considers operating conditions of the ADS transmutor, was determined by thermal-hydraulic analyses and structural analyses. When the target operates with full-power beam, a fast neutron spectrum field is formed around the target, and it is possible to apply multipurpose usage. Various research plans have been proposed, and layout of the experimental hall surrounding the target is under way. Basic physics application such as measurements of nuclear reaction data is considered as one of the major purposes.

Keywords Accelerator-driven system • J-PARC • Transmutation • Transmutation Experimental Facility

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K. Nakajima (ed.), *Nuclear Back-end and Transmutation Technology for Waste Disposal*, DOI 10.1007/978-4-431-55111-9_8

8.1 Introduction

After the Fukushima accident caused by the Great East Japan Earthquake, public interest in the management of radioactive wastes and spent nuclear fuels has increased. The Science Council of Japan recommends prioritizing research and developments to reduce the radiological burden of high-level wastes by transmutation technology.

The Japan Atomic Energy Agency (JAEA) proceeded with R&D to reduce the radiological hazard of high-level wastes by partitioning and transmutation (P-T) technology [1]. In the framework of the J-PARC project, JAEA also promoted constructing the Transmutation Experimental Facility (TEF) to study minor actinide (MA) transmutation by both fast reactors and accelerator-driven systems [2]. TEF is located at the end of the LINAC, which is also an important component to be developed for future ADS, and shares the proton beam with other experimental facilities used for material sciences, life sciences, and high-energy nuclear physics.

The TEF (Fig. 8.1) consists of two buildings, the Transmutation Physics Experimental Facility (TEF-P) [3] and the ADS Target Test Facility (TEF-T) [4]. Two facilities are connected by the proton beam line with a low-power beam extraction mechanism using a laser beam [5]. TEF-P is a facility with zero-power critical assembly wherein a low-power proton beam is available to study the reactor physics and the controllability of accelerator-driven systems (ADS). It also has availability for measuring the reaction cross sections of MA and structural materials, for example. TEF-T is planned as an irradiation test facility that can accept a maximum 400 MeV–250 kW proton beam to the lead-bismuth (Pb-Bi) spallation target. Using these two facilities, the basic physical properties of a subcritical system and engineering tests of a spallation target are to be studied.

R&Ds for important technologies required to build the facilities are also performed, such as laser charge exchange technique to extract a very low power proton beam for reactor physics experiments, a remote handling method to load MA-bearing fuel into the critical assembly, and a spallation product removal method especially for the polonium. The objectives and construction schedule of the facilities, the latest design concept, and key technologies to construct TEF are under way.

8.2 Outline of the Transmutation Experimental Facility

8.2.1 Outline of TEF-T

For the JAEA-proposed ADS, Pb-Bi is a primary candidate of coolant and spallation target. To solve technical difficulties for Pb-Bi utilization, construction of TEF-T is planned to complete the data sets that are required for the design of ADS.

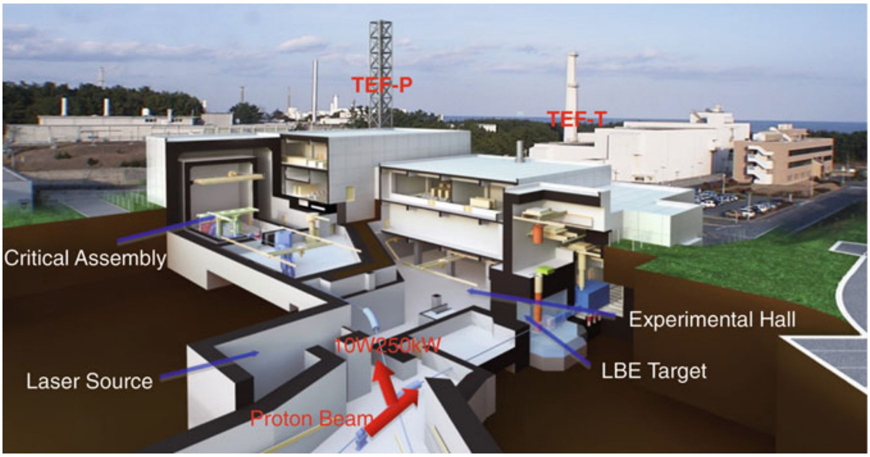

Fig. 8.1 Transmutation Experimental Facility

The experiments to obtain the material irradiation data for the beam window are the most important mission of TEF-T.

A high-power spallation target, which will be mainly used for material irradiation of candidate materials for a beam window of full-scale ADS, is an essential issue to realize a TEF-T. To set up the beam parameters, future ADS concepts are taken into account. In the reference case of the target, proton beam current density of 20 μA/cm^2, which equals the maximum beam current density of the JAEA-proposed 800 MWth ADS, was assumed.

8.2.2 Outline of TEF-P

Several neutronic experiments for ADS have been performed in both Europe [6, 7] and Japan. In Japan, subcritical experiments with fast neutron spectrum core were performed at the Fast Critical Assembly (FCA) in JAEA/Tokai, and subcritical experiments with thermal subcritical core driven by 100 MeV protons are performed at Kyoto University Research Reactor Institute. Many experimental studies also have been performed on the neutronics of the spallation neutron source with various target materials such as lead, tungsten, mercury, and uranium. These experiments for spallation targets are also useful to validate the neutronic characteristics of ADS. However, there are no experiments combined with a spallation source installed inside the subcritical fast-neutron core. The purpose of the TEF-P is divided roughly into three subjects: (1) reactor physics aspects of the subcritical core driven by a spallation source, (2) demonstration of the controllability of the subcritical core including power control by the proton beam power adjustment, and (3) investigation of the transmutation performance of the subcritical core using a certain amount of MA and LLFP.

TEF-P is designed with referring to FCA, the horizontal table–split type critical assembly with a rectangular lattice matrix. In this concept, the plate-type fuel for FCA with various simulation materials such as lead and sodium for coolant, tungsten for solid target, ZrH for moderator, B_4C for absorber, and AlN for simulating nitride fuel can be commonly used at TEF-P. Therefore, previous experiments can be correlated with TEF-P experiments. The proton beam will be introduced horizontally at the center of the fixed half assembly, and various kinds of spallation targets can be installed at various axial position of the radial center of the subcritical core. Application of MA fuel is one of the promising characteristics of TEF-P. Installation of a partial mock-up region of MA fuel with air cooling is considered to measure the physics parameters of the transmutation system. R&D to utilize MA fuel by remote handling systems is under way.

8.3 Design of Spallation Target for TEF-T

To evaluate the feasibility of a designed beam window of TEF target, numerical analysis with a three-dimensional (3D) model was performed. The analysis was done by considering the current density and shape of the incident proton beam to the target and the thermal fluid behavior of Pb-Bi around the beam window as a function of flow rate and inlet temperature. The thickness of the beam window is also considered from 2 to 3 mm. After the temperature distribution analysis, structural strength of the beam window is determined to evaluate soundness of the target. A concave shape beam window was used for this analysis. The prototype design of the beam window for TEF target system is shown in Fig. 8.2.

The material of the beam window would be a type 316 stainless steel. The concave section in the center part of the target was connected to the convex section in the terminal part, and then it was connected to the straight tube. A straight tube part has coaxially arranged annular and tube-type channels. The inner diameters of the outside tube and inside tube were set to 150 and 105 mm, respectively. The total length of the analysis region was 600 mm, which corresponds to an effective target depth for the 400 MeV proton. An irradiation sample holder, which was installed in the inner tube, holds eight irradiation specimens in the horizontal direction. The size of each specimen was $40 \times 145 \times 2$ mm. The rectification lattice having the aperture of the plural squares type was installed at the front end of the sample holder. A slit 2 mm in width was arranged along the side of the rectification lattice to cool the sample holder by flowing Pb-Bi.

The thermal-fluid behavior of the target was analyzed by the STAR-CD. The quarter-part model was set to tetra metric type and the divided face was set to a reflected image condition. At first, Pb-Bi flowed through the annular region and joined in the center of the beam window, and then, turned over and flowed in the inner tube after having passed a rectification lattice and an irradiation sample. In a default condition, flow rate at the inlet of annulus region was set to 1 l/s, and this was equivalent to the flow velocity of 0.125 m/s. Because the Pb-Bi flow forms a

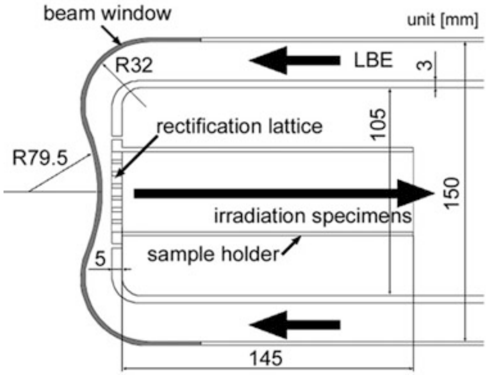

Fig. 8.2 Prototype LBE spallation target for TEF-T

complicated turbulent flow, the standard k-ε model for high Re number type was used for a turbulence model. Heat deposition distribution by the primary proton beam, which was calculated by a hadronic cascade code PHITS [8], was used for the analysis. The internal pressure to the inside of the beam window was set to 0.3 MPa in consideration of the flowing Pb-Bi and the cover gas. On the outer side of the beam window and the border of the atmosphere, release of the radiant heat was considered. Embrittlement of the structural materials by irradiation was not considered.

The analyses were performed by changing flow rates from 1 to 4 l/s. In each case, a dead region was commonly formed in the center of the inside of the beam window. The maximum velocity of Pb-Bi was confirmed at the rectification lattice part and was approximately 1.2 m/s in the case of the inlet flow rate of 1 l/s. When the inlet flow rate increased to 4 l/s, the maximum velocity in the target reached 4.8 m/s, which is too high to apply to the Pb-Bi target. The maximum temperature is 544 °C in the case of a 3-mm-thick window. The peak temperature can be decreased to 477 °C in the case of 2-mm-thick window. The temperature differences between outside and inside at the center of the window were 65 and 37 °C in the case of the 3-mm-thick window and the 2-mm-thick window, respectively. From these results, it was determined that a condition of 2 mm was desirable.

Based on the results provided by STAR-CD, analysis to verify the feasibility of the beam window was performed by ABAQUS code. The operating conditions for the first stage of material irradiation in TEF were decided by a result of the analysis on each condition. The temperature and thermal stress for the steady state were estimated using ABAQUS code, the computational code for the finite-element method. In the ABAQUS code, only a beam window was modeled as the cylinder-slab geometry. From the analysis result for the 2-mm-thick window, the stress strength reached the maximum value of 190 MPa on the outer surface of the beam window. When the maximum temperature of the beam window is adopted to 470 °C from the result of STAR-CD, maximum stress is lower than the tolerance level of the materials for fast reactor, and hence, the feasibility of a designed beam window was confirmed.

8.4 Conclusion

To perform the design study for the transmutation system of long-lived nuclides, the construction of TEF, which consists of two buildings, TEF-T and TEF-P, is proposed under the J-PARC Project. According to the current construction schedule, TEF-T will be built at the first phase and TEF-P will be constructed at the latter phase. Licensing procedures for TEF-P construction will be processed simultaneously with TEF-T construction.

TEF-T is a facility to prepare the database for engineering design of an ADS using a 400 MeV–250 kW proton beam and the Pb-Bi spallation target. The purposes of TEF-T are R&D for the structural strength of the beam window, which is irradiated by both high-energy protons and neutrons, compatibility of the structural material with flowing liquid Pb-Bi, and operation of the high-power spallation target. Several kinds of target head can be installed according to the experimental requirement. It was shown that the reference case of injected proton beam condition (400 MeV–250 kW and 20 $\mu A/cm^2$ of beam current density) was applicable to the TEF-T target. Further studies to improve irradiation performance are under way.

TEF-P is a critical assembly, which can accept the 400 MeV–10 W proton beam for the spallation neutron source. The purposes of TEF-P are the experimental validation of the data and method to predict neutronics of the fast subcritical system with spallation neutron source, demonstration of the controllability of a subcritical system driven by an accelerator, and basic research of reactor physics for transmutation of MA and LLFP. The distinguishing points of the TEF-P in comparison with existing experimental facilities can be summarized as follows: (1) both the high-energy proton beam and the nuclear fuel are available, (2) the maximum neutron source intensity of about 10^{12} n/s is strong enough to perform precise measurements even in the deep subcritical state (e.g., $k_{\mathrm{eff}} = 0.90$) and is low enough to easily access the assembly after the irradiation, (3) a wide range of pulse width (1 ns–0.5 ms) is available by the laser charge exchange technique, (4) MA and LLFP can be used as a shape of foil, sample, and fuel by installing an appropriate shielding and remote handling devices.

Along with the design study of the TEF, R&D for the components required for TEF, such as the laser charge exchange technique to extract a very low power proton beam, test manufacturing of MA fuel-handling devices, and operation of lead-bismuth test loops are under way. From the experimental results of the laser charge exchange technique, beam extraction in the magnetic field is successfully demonstrated. Mockup of the coolant simulator block and remote handling mechanism for pin-type fuel loading has been done. An effective method to remove polonium with a standard stainless mesh filter was established through the hot experiments. Significant improvement of analysis accuracy of actual ADS was expected by critical experiment with MA fuel at TEF-P.

When the target of TEF-T operates with a full power beam, a fast neutron spectrum field is formed around the target and it is possible to apply multipurpose usage. Various research plans have been proposed, and layout of the experimental hall surrounding the target is under way. Basic physics application such as measurements of nuclear reaction data is considered as one of the major purposes. We called for a preliminary letter of intent to encourage the project. Requests for multipurpose usage will be taken into account in the facility design of TEF.

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